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Contaminant Distribution Around Persons in Rooms Ventilated by Displacement Ventilation

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INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 40

Presented at ROOMVENT '94, Fourth International Conference on Air Distribution in Rooms, June 15-17, 1994, Cracow, Poland

H. BROHUS, P. V. NIELSEN
CONTAMINANT DISTRIBUTION AROUND PERSONS IN ROOMS VENTILATED BY DISPLACEMENT VENTILATION
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SUMMARY

An optimal design of the ventilation system needs a proper prediction of the velocity, temperature and contaminant distribution in the room. Traditionally this is done either by the use of simplified models or by a somewhat more comprehensive CFD-simulation. Common to both methods is usually the lack of consideration for the persons present in the room. This paper deals with some of the effects of persons present in a displacement ventilated room, especially the effect on the contaminant distribution.

It is demonstrated that although the contaminant distribution is affected the stratification in the flow is stable when people are moving around in the room.

The exposure of a sitting and a standing person in proportion to the stratification height is examined. It is found that the flow in the boundary layer along a person to a great extent is able to entrain air from below the breathing zone. Measurements also show the possible disadvantage when contaminant sources are located in the lower part of the room.

Two new quantities, applied in connection with personal exposure in ventilated rooms, are defined.

CONTAMINANT DISTRIBUTION AROUND PERSONS IN ROOMS VENTILATED BY DISPLACEMENT VENTILATION

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1. INTRODUCTION

During recent years displacement ventilation has become an often used way to ventilate offices and industrial buildings, especially in the Scandinavian countries. With this there is an increasing demand for energy efficient design which, at the same time, is able to ensure a high level of thermal comfort and indoor air quality.

An optimal design of the ventilation system needs a proper prediction of the velocity, temperature and contaminant distribution in the room. Traditionally this is done either by the use of simplified models or by a somewhat more comprehensive CFD-simulation. Common to both methods is usually the lack of consideration for the persons present in the room.

A person produces heat due to the metabolism and the surface temperature is usually several degrees above the ambient temperature level. In a state of thermal comfort the temperature of the human skin is about 33 - 34°C depending on the activity level [1]. The clothing forms an insulating layer between the skin and the surrounding air and causes a drop in surface temperature. The temperature drop may be 5 - 8°C for persons standing relaxed wearing usual indoor clothing. The resulting excess temperature causes an upward air flow along the body which entrains air from the surroundings.

The boundary layer around the person is able to entrain and to transport clean air as well as contaminated air to the breathing zone which may cause an exposure to pollution in the room. Another effect of persons in ventilated rooms is the disturbance caused by movements. When displacement ventilation is applied the influence on the stratification of the flow is especially important.

In this paper the topics mentioned above are discussed and full-scale measurements are presented showing different aspects of persons present in a displacement ventilated room.

2. EXPERIMENTAL SET-UP

2.1. Full-scale test rooms

The measurements reported are performed in three full-scale test rooms with a length, width and height, respectively:

Small test room 1	4.2 m x 3.6 m x 2.4 m
Small test room 2	5.4 m x 3.6 m x 2.6 m
Large test room	8 m x 6 m x 4 m

Three different wall-mounted low-velocity inlet devices are used. They are shown in figure 1. The return opening in the small test room 1 is located at the corner of the room in the wall 0.15 m below the ceiling. In the other rooms the return openings are located in the ceiling.

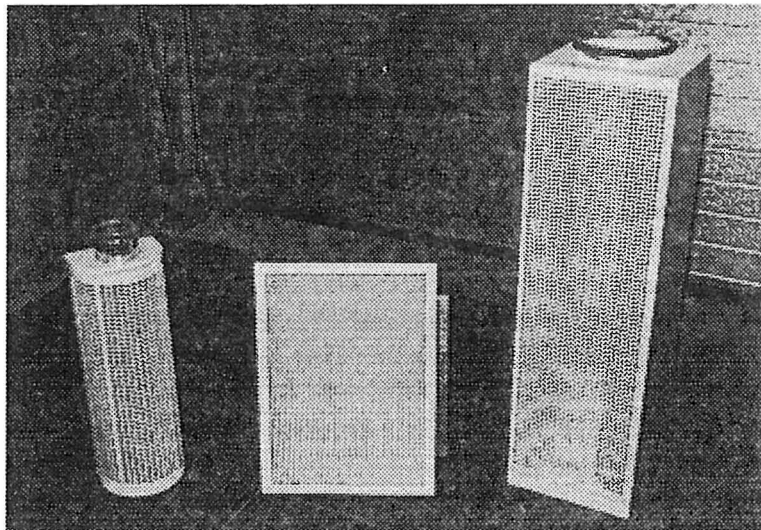


Fig. 1. Low-velocity inlet devices used in the three full-scale test rooms. The devices are used in the small test room 1 (left), small test room 2 (centre) and in the large test room (right), respectively.

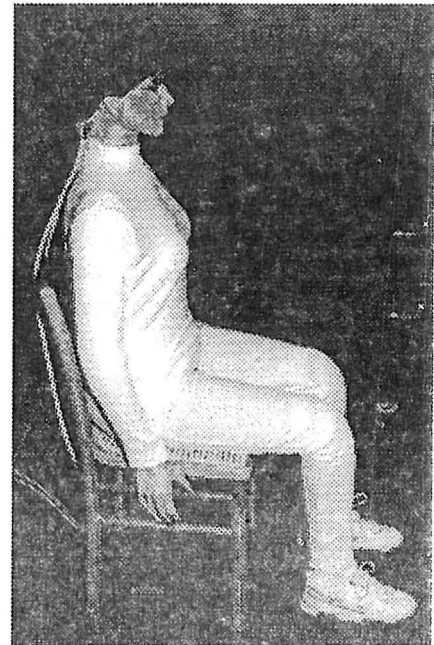
2.2. Heat sources

Three different heat sources are used. A point heat source consisting of heated coils mounted on an iron base surrounded by a 0.2 m high tube \varnothing 0.15 m. A person simulator in shape of a 1.0 m high black-painted closed cylinder \varnothing 0.4 m, heated by four light bulbs. Finally a thermal manikin acts as a heat source.

2.3. Thermal manikin

To be able to measure the personal exposure properly the thermal manikin seen on figure 2 is used. The manikin is shaped as a 1.7 m high average sized woman. The tight-fitting clothes have an insulation value of 0.8 clo.

Fig.2. Thermal manikin used to measure the personal exposure etc. The manikin is separated in 16 individually controlled parts of the body, each with the same surface temperature and heat output as people in thermal comfort. An artificial lung provides for the breathing.



The manikin consists of a fibre armed polyester shell, wound with nickel wire used sequentially both for the heating of the manikin and for measuring and controlling the skin temperature. The skin temperature and the heat output correspond to people in thermal comfort.

An artificial lung provides for the breathing. It is possible to adjust both the frequency of respiration (number of breaths per minute) and the pulmonary ventilation (litres per minute).

3. RESULTS AND DISCUSSION

3.1. Thermal and passive sources

The location of the contaminant source in the room has a great impact on the concentration distribution and with it the personal exposure.

In figure 3 the concentration profiles for two different locations of the source are shown.

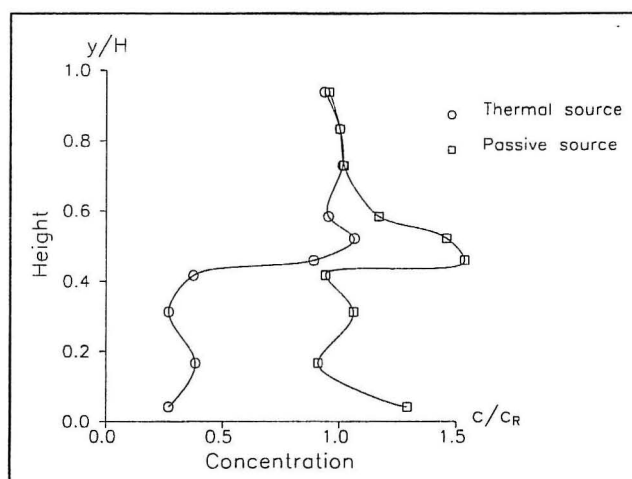


Fig. 3. Concentration profiles measured in the small test room 1 with a thermal (○) and a passive (□) contaminant source. The room is ventilated after the displacement principle with an air change rate of 5 h^{-1} and a heat load of 400 W supplied by four person simulators. The neutral density tracer gas is CO_2 mixed with He.

Figure 3 shows concentration measurements performed in the displacement ventilated small test room 1. The air change rate is 5 h^{-1} and the heat load is 400 W supplied by four person simulators.

The vertical concentration profile in the room is measured by a thermal and a passive contaminant source. The thermal source is established by supplying the tracer gas in the plumes above the four person simulators. The passive source is established by supplying tracer gas outside the plumes 0.5 m above the floor near the centre of the room. In both cases the tracer gas is supplied by a ping-pong ball with six evenly distributed holes at neutral density.

The stratification in the displacement ventilated room is clearly seen on the concentration profile when the thermal source is applied. In this case the displacement principle works very well. A concentration gradient is established in the room where the air in the upper part is separated from the less contaminated air in the lower part.

However, when the passive contaminant source is located in the lower part of the room it lacks any buoyancy or momentum to raise it above the stratification height. The vertical concentration profile reveals that the dimensionless concentrations approach 1 corresponding to complete mixing. Pollutants generated in neutral places of the room cause considerable local concentrations which may be entrained into the boundary layer of the present persons giving rise to exposure as pointed out by Holmberg et al. (1987) and Nielsen (1993).

As demonstrated it is important to supply the tracer properly to ensure that a contaminant source assumed to be thermal, really becomes a thermal source in practice, ditto passive sources.

3.2. Convection around sources

The contaminant transport is governed by diffusion and convection. Even a rather low velocity around the contaminant source may result in a convection dominated dispersion. This fact has great impact on the propagation of contamination in displacement ventilated rooms because of the stratified flow where the velocity field alters in vertical direction due to the reverse flow as shown in figure 4.

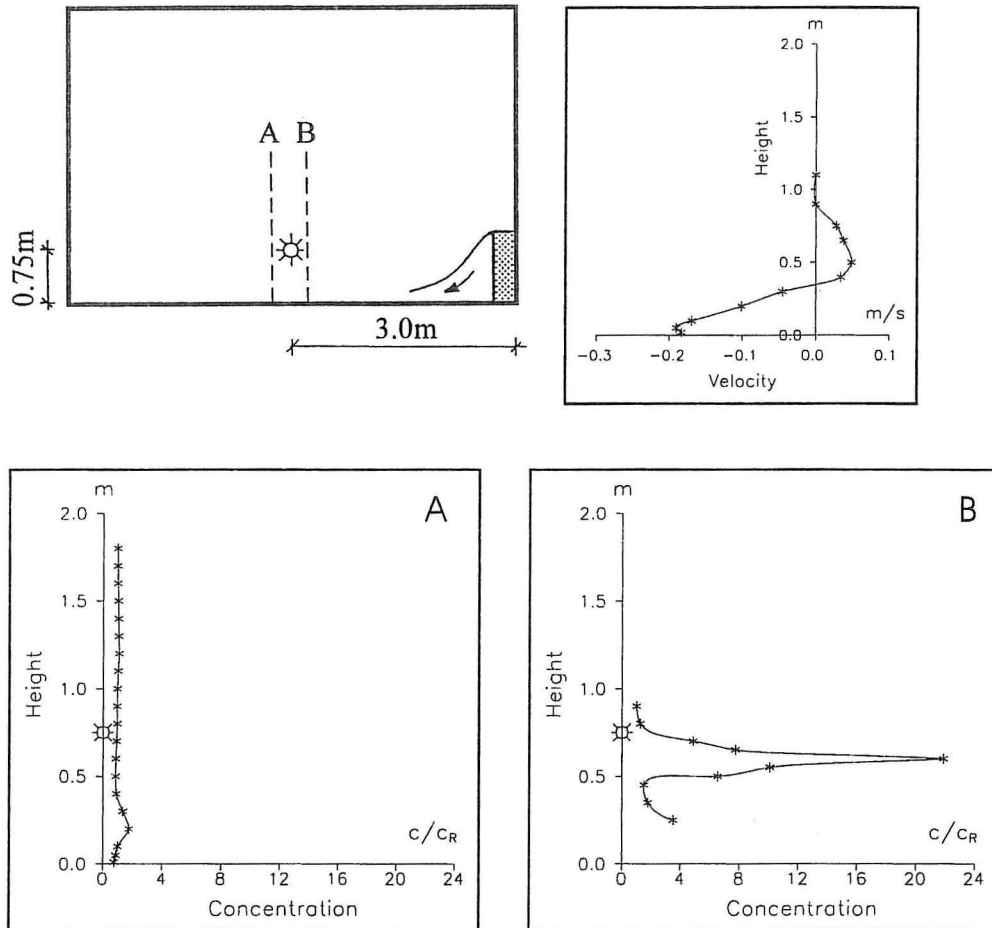


Fig. 4. Velocity and concentration profiles from the displacement ventilated large test room. The velocity profile is measured 3.0 m from the inlet device at the same location as the contaminant source. Two concentration profiles are measured. 0.1 m upstream the source (A) and 0.1 m downstream the source (B). The neutral density tracer gas is N_2O mixed with He. Air change rate is 1.5 h^{-1} and heat load is 400 W.

As indicated in figure 4 the source is located 0.75 m above the floor in the reverse flow of the displacement ventilated large test room. The air change rate is 1.5 h^{-1} and the heat load is approximately 400 W generated by two person simulators, a point heat source and the thermal manikin. The measurements are performed at steady state.

The velocity profile is measured at the same location as the contaminant source. It is seen that the velocity at the height of the source is below 0.05 m/s. Two concentration profiles are measured, one at the upstream side and the other at the downstream side of the contaminant source, both at a distance of 0.1 m. The concentration profiles demonstrate the influence of the convective mass transfer. Even at a velocity below 0.05 m/s the diffusion is dominated extensively by the convective transport. Figure 4 indicates that the vertical location of the contaminant source in a displacement ventilated room may be an important parameter to consider if the source is found in the lower part of the room. Even a vertical difference of few centimetres may give rise to somewhat deviating results.

3.3. Persons' impact on stratification

The displacement principle is usually chosen to achieve an energy efficient ventilation system capable to ensure a high level of thermal comfort and indoor air quality. A basis for meeting the demands is the stratification of the temperature and the concentration fields in the displacement ventilated room. When there is no disturbance from movements in the room the displacement principle may work well, but will moving persons or machinery be able to destroy or affect the stratification? Results from full-scale measurements on the topic are shown below.

To describe the efficiency of an air distribution system different quantities are commonly used. The ventilation effectiveness ϵ_{oc} in the occupied zone is given by

$$\epsilon_{oc} = \frac{c_R}{c_{oc}} \quad (1)$$

where c_R is the concentration in the return opening and c_{oc} is the mean concentration in the occupied zone. In this paper the occupied zone is defined as the area up to 1.8 m above floor level.

The local ventilation index ϵ_P is defined as

$$\epsilon_P = \frac{c_R}{c_P} \quad (2)$$

where c_P is the concentration in a point of the room.

A new effectiveness is defined, the inhalation effectiveness ϵ_e

$$\epsilon_e = \frac{c_R}{c_e} \quad (3)$$

where c_e is the concentration in the air inhaled by a person. c_e is also an indication of the exposure to contamination in the room. If the pulmonary ventilation is known it is possible to calculate the amount of inhaled matter.

Equations (1) to (3) assume that the supply air is uncontaminated.

The temperature effectiveness in the occupied zone ϵ_T is defined as

$$\epsilon_T = \frac{T_R - T_0}{T_{oc} - T_0} \quad (4)$$

where T_R , T_0 and T_{oc} are the temperature in the return opening, the temperature in the supply opening and the mean temperature in the occupied zone, respectively.

To examine the influence on stratification from moving persons concentration and temperature measurements are performed in the small test room 1 and the small test room 2.

In figure 5 concentration profiles are found in three different cases where the heat sources and the contaminant sources are constituted by four person simulators (\circ), four sitting persons (\square) and four persons of whom two are sitting and two are walking about in the room (\triangle).

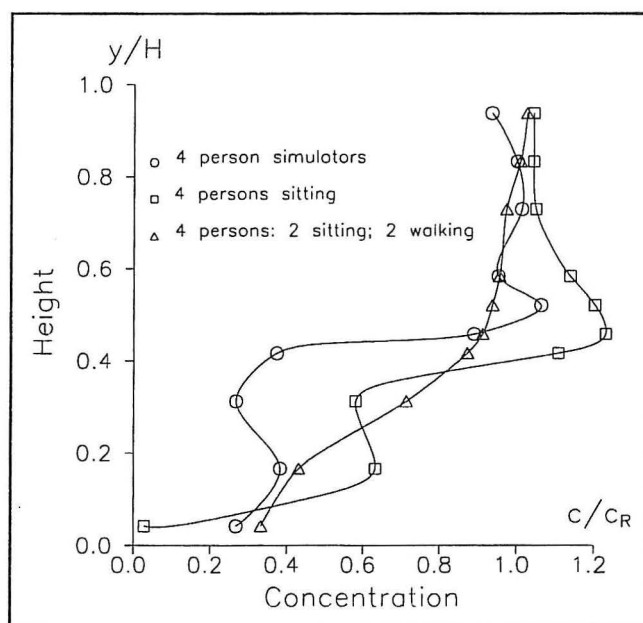


Fig. 5. Concentration profiles in the displacement ventilated small test room 1. Air change rate is 5 h^{-1} and heat load is 400 W and 600 W (\triangle). Heat and contaminant sources are four person simulators (\circ), four sitting persons (\square) and four persons of whom two are sitting and two are walking about (\triangle). CO_2 mixed with He is used as tracer gas in the case of person simulator measurements. In the other two cases the persons supply the tracer by the respiration.

In the case of four person simulators (○) the stratification is very distinct showing the separation of the cleaner lower part of the room and the more contaminated upper part. When the simulators are replaced by four persons the concentration profile changes and a tendency of smoothing is seen.

The ventilation effectiveness in the occupied zone ϵ_{oc} is 1.68 (○), 1.25 (□) and 1.38 (△), respectively. Some deviation between the case of simulators and the case of persons is found, while the effectiveness in the case of four sitting persons approaches the case of two persons sitting and two persons walking about. This indicates that neither moving persons nor sedentary persons are able to destroy or to disturb the stratification considerable in the previous case. The movements were restrained to usual indoor walking and presumably, more intense activity would manage to affect the concentration field to a greater extent as reported by Mundt (1993) where transient disturbances such as the opening and closing of a door are addressed.

Disturbance of the temperature field due to movements is examined in the two small test rooms with person simulators as well as sitting and moving persons.

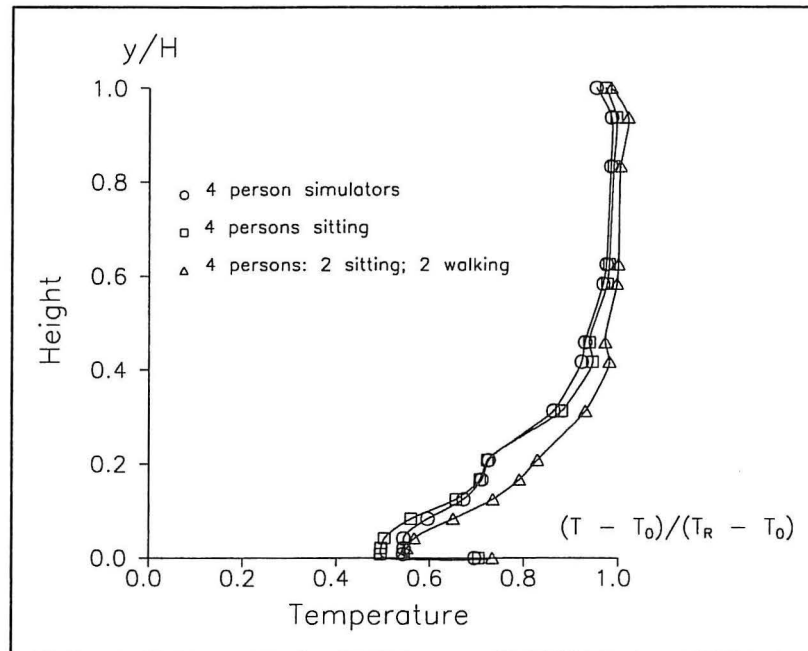


Fig. 6. Temperature profiles in the displacement ventilated small test room 1. Same conditions as figure in 5. Four person simulators (○), four sitting persons (□) and four persons of whom two are sitting and two are walking about (△).

Figure 6 shows the dimensionless temperature profiles corresponding to the concentration profiles in figure 5. From the temperature profiles a rather good agreement between the measurements with the four person simulators (○) and the four persons sitting (□) is found.

When the two of the four persons are walking about in the room (Δ) the profile shows a slight deviation towards the state of complete mixing, i.e. a dimensionless temperature on 1 throughout the room.

The temperature effectiveness for the occupied zone ϵ_T is 1.20 in the case of four simulators as well as four sitting persons, while the effectiveness amounts to 1.13 in the case of two persons sitting and two persons in motion (Δ). As expected the effectiveness becomes the smallest during the movements. Although the profile changes, there is only a minor influence on the stratification due to the disturbance in the previous case.

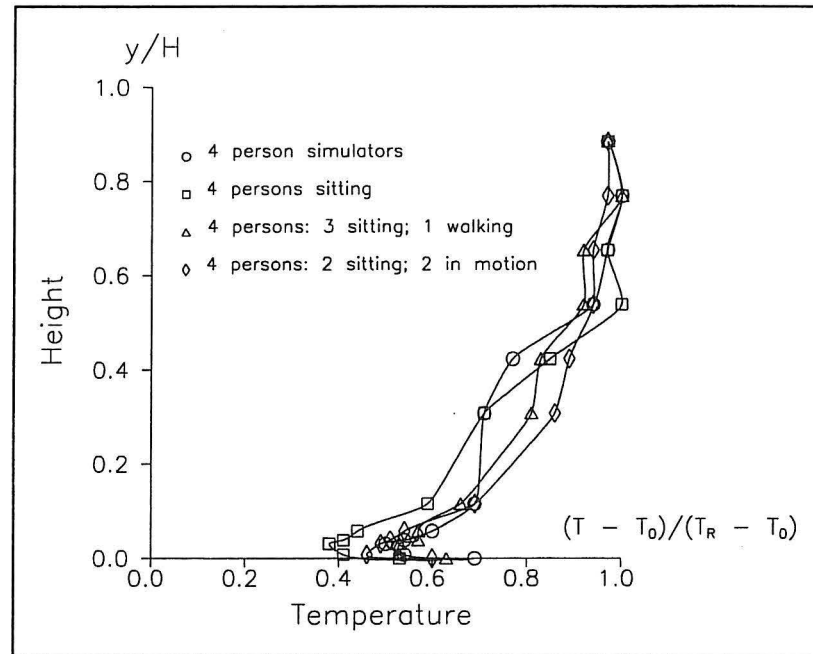


Fig. 7. Temperature profiles in the displacement ventilated small test room 2. Air change rate is 7.6 h^{-1} and heat load is approximately 400 W. Heat sources are four person simulators (\circ), four sitting persons (\square), three persons sitting and one walking about (Δ) and two persons sitting and two in motion (\diamond). Phan and Schulz (1991).

In the small test room 2 measurements, almost similar to the previous ones, are shown in figure 7. Also in this case four person simulators (\circ) and four sitting persons (\square) take part, but now there are two different patterns of movement. In the one case three person are sitting while one person is walking about (Δ). In the other case two persons are sitting while two persons are walking about interrupted by heavy movements of the arms and slight exercises (\diamond).

The temperature effectiveness in the occupied zone is 1.99 (\circ), 1.73 (\square), 1.70 (Δ) and 1.60 (\diamond), respectively.

The effectiveness from these measurements is not directly comparable to the effectiveness corresponding to figure 6 because of different inlet devices, air change rates and Archimedes numbers, but the tendencies are the same. The maximum effectiveness is obtained when the disturbance is the slightest and the effectiveness decreases when the movements in the room increase.

Summarizing it must be concluded that even intense movements in the displacement ventilated room are not able to destroy the temperature stratification, but the temperature effectiveness shows a slight decrease when disturbance in the room increases. The concentration stratification seems to be more sensitive to persons' movements. The disturbance created may smoothen the gradient to some extent, which is also pointed out by Nielsen (1992). Heavy movements may cause a mixing of the upper contaminated zone and the lower cleaner zone, i.e. $\epsilon_{oc} \sim 1$.

3.4. Personal exposure to contaminants

As mentioned previously one of the purposes of displacement ventilation is to provide a good indoor air quality for the persons in the room.

The indoor air quality exerts influence on persons due to the breathing. Both from a health point of view as well as a perceived air quality point of view, the influence arises from the inspired air. Therefore, it is more relevant to know the concentration of the contaminant in the inhaled air than the concentration at a neutral place of the room measured at the same height.

Often the exposure in a ventilated room is estimated from the concentration measured in the height of the breathing zone in a neutral place of the room. This may be a good approximation in mixing ventilated rooms, but when displacement is applied this may lead to erroneous exposures. The reason is the combined effect of the entrainment of room air into the human boundary layer and the concentration gradients in the displacement ventilated room.

The transport of fresh air as well as contaminated air in the boundary layer may cause the concentration in the inhaled air to deviate considerably from the air outside the breathing zone measured at the same height.

Subsequently, the above-mentioned topics are discussed by means of the full-scale measurements on personal exposure in a displacement ventilated room at different stratification heights and pollutant source locations.

3.4.1. Exposure in proportion to stratification height

In the following "exposure" is defined as the contaminant concentration in the inhaled air c_e . The exposure measurements are performed with the thermal manikin by means of an artificial lung able to provide the respiration either through the mouth or through the nose. Since the manikin is controlled to obtain the same heat output and the same skin temperatures as a human being under the same circumstances, the results are, to a great

extent, supposed to approach the personal exposure of a real person. Certain limitations are discussed later.

Exposure measurements are carried out with respiration through the mouth. In the present measurements no significant difference between respiration through the mouth and respiration through the nose is found. The present measurements are performed at steady state conditions.

The real exposure to a certain matter in a room requires detailed time dependent knowledge of the pulmonary ventilation and the pattern of movements besides c_e .

In figure 9 the exposure of a sitting and a standing manikin is shown. The measurements are performed in the large full-scale test room at three different stratification heights y_{st} . The corresponding temperature and velocity profiles are found in figure 8.

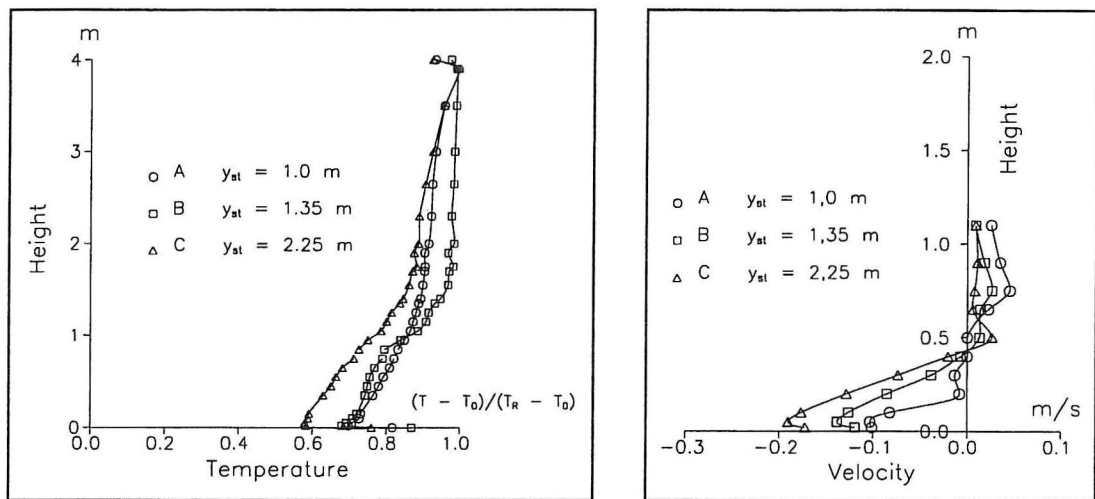


Fig. 8. Temperature and velocity profiles in the displacement ventilated large test room. The measurements corresponds to the concentration measurements in figure 9. The velocity profiles are measured 4.0 m from the inlet device at the same location as the thermal manikin. q is the airflow rate, Φ is heat load and ΔT is the temperature difference between inlet and outlet.

Please note the different ordinate axis heights.

Case A: $y_{st} = 1.00$ m, $q = 145$ m³/h (0.8 h⁻¹), $\Phi = 771$ W, $\Delta T = 9.8$ °C

Case B: $y_{st} = 1.35$ m, $q = 290$ m³/h (1.5 h⁻¹), $\Phi = 376$ W, $\Delta T = 5.0$ °C

Case C: $y_{st} = 2.25$ m, $q = 395$ m³/h (2.1 h⁻¹), $\Phi = 781$ W, $\Delta T = 7.6$ °C

Measurements are carried out in collaboration with Christensen and Stevnhoved (1993).

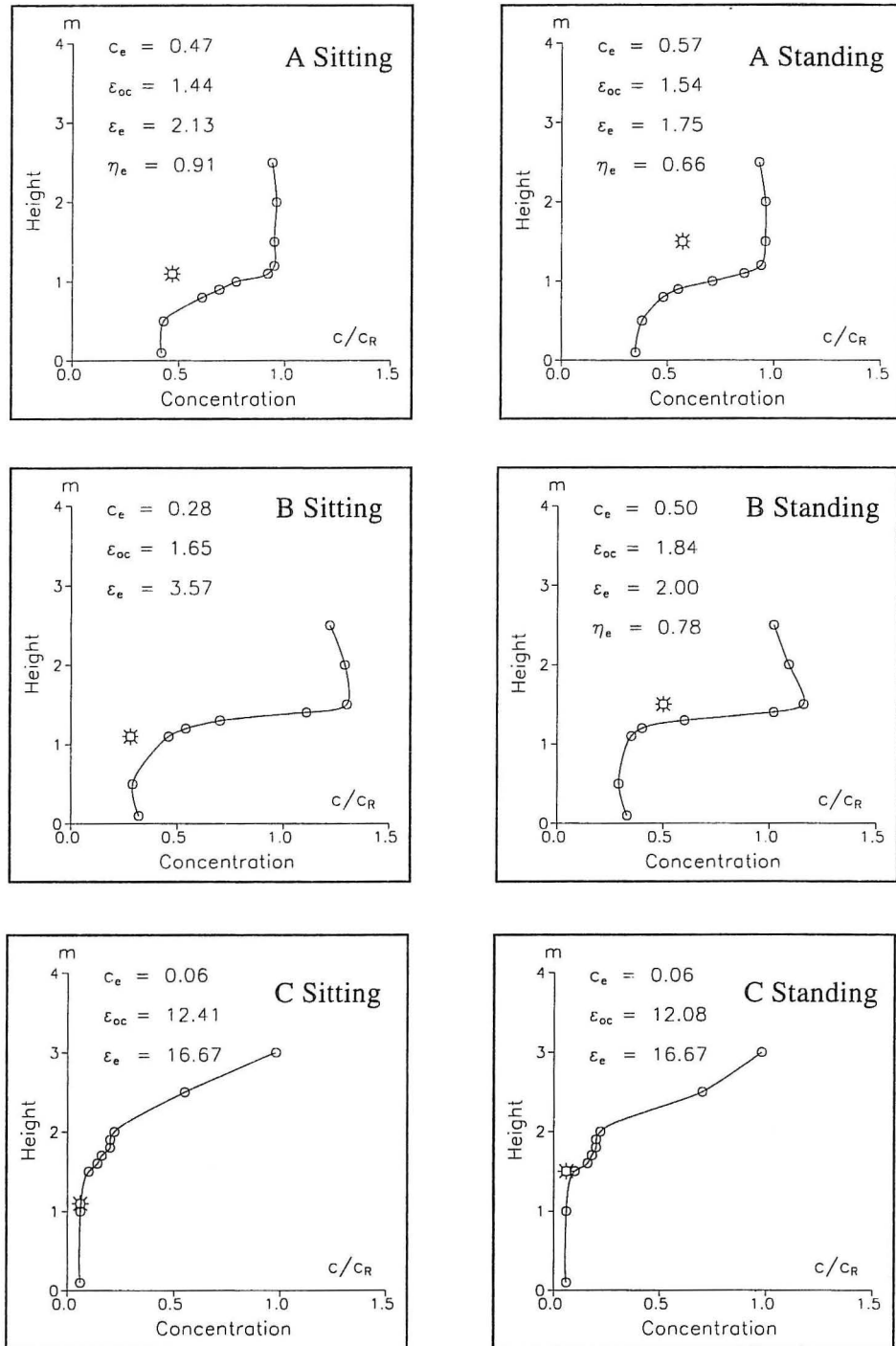


Fig. 9. Personal exposure in the displacement ventilated large test room. Exposure (\star) and concentration (\circ) are shown at the stratification heights 1.0m (A), 1.35m (B) and 2.25m (C) for sitting (left) and standing (right) manikin. Exposure c_e , effectiveness in the occupied zone ε_{oc} , inhalation effectiveness ε_e and effectiveness of entrainment in the human boundary layer η_e . The tracer gas CO_2 is supplied above a heat source. Measurements in collaboration with [7].

Figure 9 shows the concentration profile (\circ) and the exposure (\otimes) at the three stratification heights 1.0 m (A top of figure), 1.35 m (B middle of figure) and 2.25 m (C bottom of figure). In all three cases the thermal manikin (approximately 75 W), the two person simulators (2 x 100 W) and the point heat source (100 or 500 W) constitute the heat load in the room. Due to the uninsulated walls there is a slight heat transfer between the room and the surrounding laboratory, which is presumably of no particular importance.

As seen in figure 9 the effect of entrainment and transport of room air from the lower and cleaner zone to the breathing zone is distinct, which is also pointed out by Holmberg et al. (1990). This means that the concentration in the inhaled air c_e is smaller than the corresponding concentration in the same height at a neutral place of the room. In this case the entrainment provides a better indoor air quality in the displacement ventilated room than in the case of mixing ventilation.

In figure 9 the exposure c_e , the effectiveness in the occupied zone ϵ_{oc} and the inhalation effectiveness ϵ_e for the three cases are mentioned. The figure shows that the effectiveness in the occupied zone is higher than in the case of mixing ventilation, where ϵ_{oc} approaches 1 in the ideal case. As expected the effectiveness increases with an increasing stratification height. In all cases the inhalation effectiveness ϵ_e exceeds ϵ_{oc} , indicating that the quality of the inhaled air exceeds the mean air quality in the occupied zone.

As revealed, the exposure is much depending on the concentration in the lower zone of the room. This concentration may vary (at the same stratification height) from case to case depending on inlet device, heat sources, Archimedes number etc. Therefore a new quantity is defined, the effectiveness of entrainment in the human boundary layer, designated η_e .

$$\eta_e = \frac{c_p - c_e}{c_p - c_f} \quad (5)$$

where c_f is the concentration at the floor which typically corresponds to the concentration in the lower, cleaner zone of the displacement ventilated room.

The effectiveness of entrainment in the human boundary layer η_e , expresses the ability to supply (fresh) air from the floor area to the breathing zone. It expresses the utilized fraction ($c_p - c_e$) of the possible concentration difference ($c_p - c_f$).

When η_e is 1 all the inhaled air comes from the lower zone (c_e equals the concentration at the floor). When η_e is 0 the concentration in the inhaled air c_e equals the concentration at a neutral place at the same height c_p , i.e. no particular effect because of the convective transport in the human boundary layer. In the case of complete mixing as well as the case of ideal displacement ventilation with a stratification height located above the breathing zone, η_e is not defined. In these cases c_e equals the homogeneous concentration in the lower zone.

One of the advantages of η_e is the independence of the concentration in the lower zone which may be specific in separate cases. With it an improved possibility of comparing results from different test rooms and different set-ups arises.

In figure 9 η_e is shown for case A and case B-standing where η_e is defined. The figure illustrates to what extent the inhaled air is supplied from the lower and cleaner zone. In case A-sitting almost all air comes from the lower zone, while in case A-standing only a little more than half of the air arises from there. The reason why η_e is lower in the case A-standing is obviously that the breathing zone is located at a higher level, and as a consequence more contaminated air is entrained in the boundary layer before it reaches the breathing zone where it is inhaled.

Holmberg et al. (1990) have performed measurements with four person simulators and four persons in a displacement ventilated room at a stratification height of 0.7 m. If the effectiveness of entrainment in the human boundary layer η_e is calculated using these measurements the following results are obtained. In the case of four person simulators η_e is 0.78 and in the case of four sitting motionless persons and four sitting persons in natural motion η_e amounts to 0.94 and 0.66, respectively. The case of the present measurements which is getting closest to the above-mentioned conditions is the case A-sitting where η_e is 0.91. This has to be compared with 0.94 (motionless sitting persons and $y_{st} = 0.7$ m). Despite the different room sizes, inlet devices, heat sources and persons versus a thermal manikin a fair agreement is found.

One disadvantage of the thermal manikin exposure measurements is presumably the immobility of the manikin. In ventilated rooms with real persons there will always be some motion and disturbance. This point is supported by the measurements of Holmberg et al. (1990), where η_e changed from 0.94 to 0.66 when the four persons changed from motionless to natural motion in sitting posture. This indicates what is previously mentioned, that movements decrease the ventilation effectiveness in the occupied zone resulting in increased mixing and increased exposure. In the extreme case when a person moves very fast through a displacement ventilated room the exposure c_e approaches c_p even though the stratification is very stable because of the huge disturbance of the boundary layer along the person and the considerable horizontal velocity generated around the breathing zone.

Measurements concerning movements are at the present time performed by means of the thermal manikin placed in a wind channel. The effect of movements on the manikin is assumed to be equivalent to the impact from the uniform velocity field. The measurements show a significant influence from the velocity field on the human boundary layer and with it an influence on the ability to transport fresh air as well as contaminated air upwards to the breathing zone, i.e. η_e decreases when movements increase.

3.4.2. Exposure in proportion to point contaminant source location

Apart from personal exposure due to the general concentration distribution in the displacement ventilated room (3.4.1.) the effect of a point contaminant source location on the exposure may be important. In figure 10 the exposure of a standing thermal manikin is found in the case of a high and a low location of a point contaminant source.

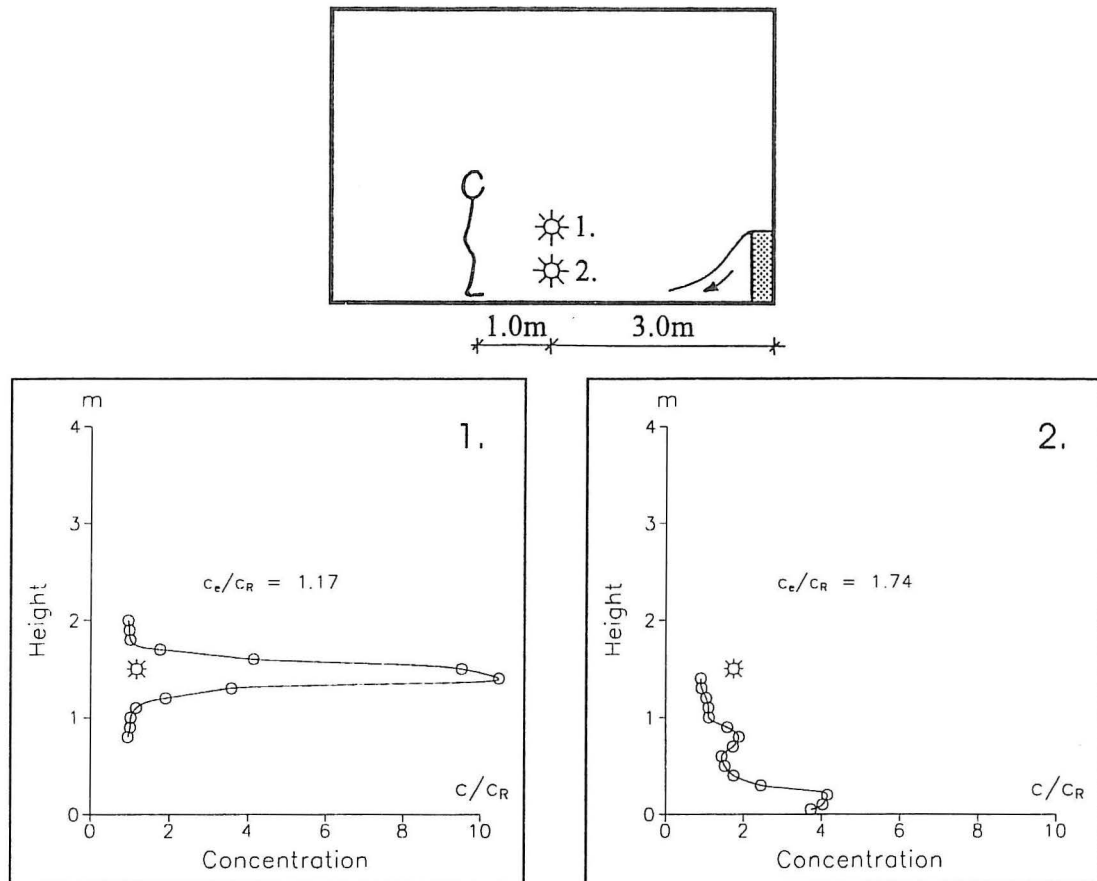


Fig. 10. Personal exposure (⊗) at concentration profiles (○) corresponding to a high (1) and a low (2) location of a point contaminant source in the displacement ventilated large test room. The concentration profile is measured 0.9 m from the manikin. The measurements are performed at conditions corresponding to case B (see figure 8). Neutral density tracer gas is N_2O mixed with He supplied through a porous foam rubber ball.

Figure 10 shows the effect of two different concentration distributions corresponding to different point source locations. In the case of high location of the source (1) c_e is 1.17 which must be considered rather low compared with the high concentration peak in the height of the breathing zone. However, in the case of low location of the source (2), the exposure amounts to 1.74 while the concentration in the height of the breathing zone approaches 1. This reveals the advantage and the disadvantage of entrainment and transport in the human boundary layer. In case 1 the boundary layer transports fresh air to the breathing zone and only slight influence from the very high local concentration in the

breathing zone height is seen. In case 2 the boundary layer obviously transports contaminated air to the breathing zone even though no particular high concentration is found in the breathing zone height at a distance of 0.9 m.

The influence on personal exposure in proportion to the point source height is examined in figure 11. Two different cases are investigated, the manikin standing facing the inlet device (1) and the manikin standing reversed (2) as shown in figure 11.

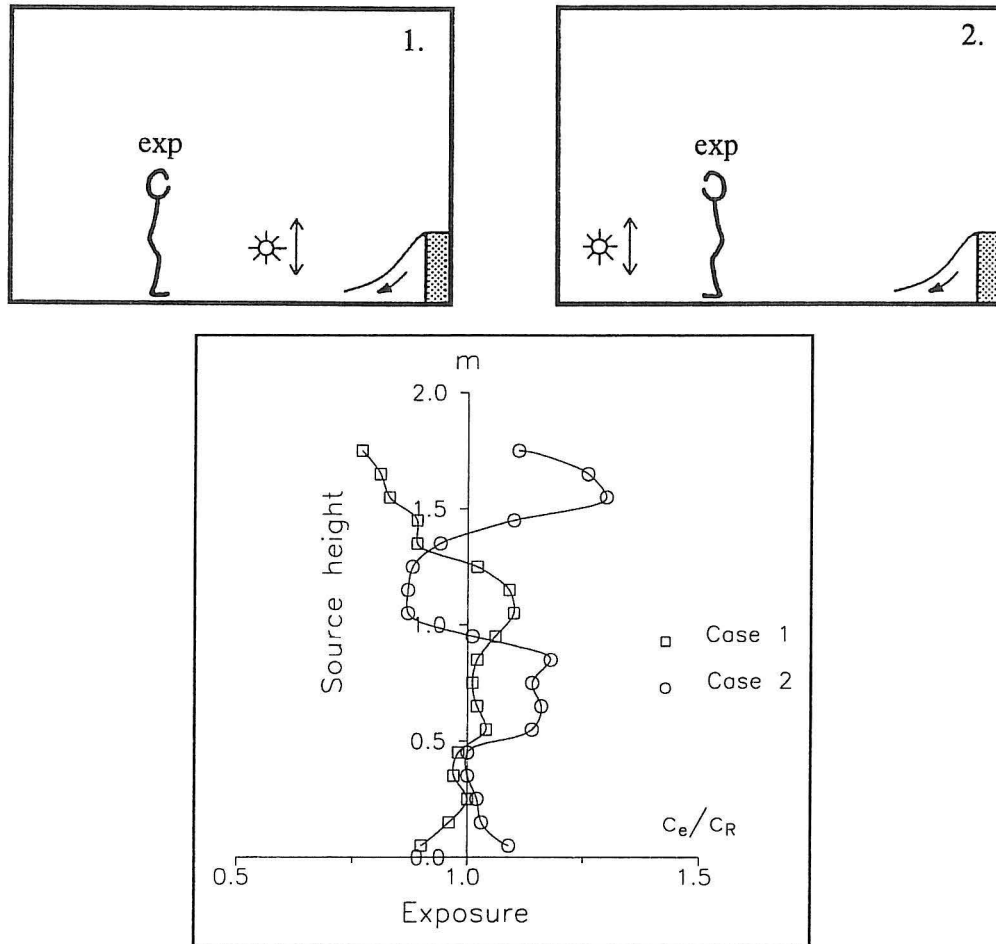


Fig. 11. Personal exposure c_e as a function of point contaminant source height in the displacement ventilated large test room. The vertical distance between the source and the manikin is 1.5 m. Case 1, manikin facing inlet device (\square) and case 2, manikin reversed (\circ). The measurements are performed at conditions corresponding to case B (see figure 8). Neutral density tracer gas is N_2O mixed with He supplied through a porous foam rubber ball.

Figure 11 shows how the exposure c_e clearly varies with the elevation of the point source in the room. Both improved as well as deteriorated indoor air quality proportional to the case of complete mixing is found. A distinct dependence on the flow field stresses the importance of the convective mass transport when pollutant dispersion is addressed (see figure 4).

When the manikin, still facing the source located 1.5 m away, is turned around (2) the exposure is almost opposite the previous case (1) as if mirrored in the ordinate axis of figure 11. In the one case the vertical convective flow removes the contamination either giving rise to improved ($c_e < 1$) or somewhat mixed conditions ($c_e \sim 1$) in the lower zone. In the other case the vertical convective flow transports the contamination directly against the manikin where a fraction is entrained in the boundary layer giving rise to enhanced exposure ($c_e > 1$). Actually, this result may to some extent be expected when the flow stratification is considered (main flow at the floor, reverse flow above etc.).

To illustrate the route of the contaminant in the boundary layer measurements are performed on the contaminant concentration at the chest and the contaminant concentration at the back in proportion to the point source height. The conditions are otherwise the same as in case 2 in figure 11.

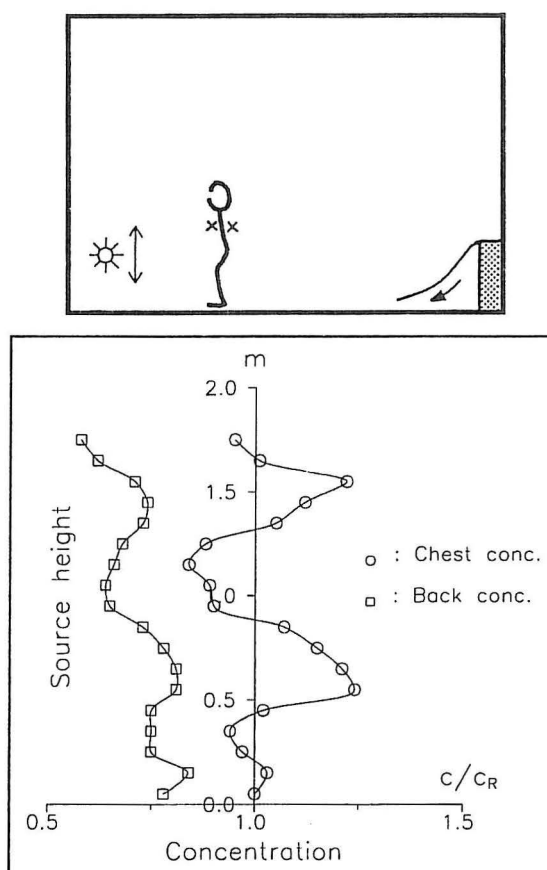


Fig. 12. Concentrations measured at the chest (\circ) and the back (\square) at a distance of 0.3 m from a virtual point between the ears of the person. The concentrations are found as a function of the point source height. The conditions are otherwise the same as case 2 in figure 11.

The two concentrations (\circ) and (\square) in figure 12 are measured at the same height of the room. If the person was not present they would be approximately the same, while in the actual case there is a significant difference. What makes the difference is the presence of a person and the entrainment and transport of the contaminant as well as the fresh air in the human boundary layer.

If the concentration at the chest (\circ) is compared with the exposure c_e in case 2 figure 11 a very good correspondence is seen, due to the fact that the main part of the inhaled air comes from the boundary layer in front of the person, anyhow, in the case of an almost motionless person in a room where the velocities from the air distribution system are sufficiently low to avoid draught and to ensure thermal comfort.

The measurements show the effect of persons' facing relative to the inlet device and the point contaminant source. If the manikin was turned around to face the inlet, the exposure might presumably be reduced 25% in the present case.

The topic of concentration distribution at different contaminant source locations in a displacement ventilated room is also discussed by Stymne et al. (1991), where measurements are performed by means of a passive tracer gas technique.

4. CONCLUSIONS

Persons present in a displacement ventilated room may influence the air distribution to some extent and vice versa the ventilation influence the persons.

It is demonstrated that although the contaminant distribution is affected the stratification in the flow is stable when people are moving around in the room. The temperature field is shown to be somewhat more stable than the concentration field. When movement and disturbance in the room increase the ventilation effectiveness decreases and the exposure increases.

The exposure of a sitting and a standing person as a function of the stratification height is examined. It is found that the flow in the boundary layer along a person, to a great extent, is able to entrain air from below the breathing zone improving the quality of the inhaled air.

Persons' movements causes the air quality to decrease due to the disturbance of the stratification as well as the disturbance of the human boundary layer which promotes the high air quality transporting fresh air to the breathing zone.

Entrainment of air in the human boundary layer is usually an advantage, but measurements also show the possible disadvantage when contaminant sources in the lower part of the room are present. In this case the plume around the person transports contamin-ated air to the breathing zone giving rise to increased exposure.

Two new quantities are defined:

- The inhalation effectiveness ϵ_e which expresses the concentration of the air inhaled by the person relative to the return concentration.

- The effectiveness of entrainment in the human boundary layer η_e which expresses the ability to supply (fresh) air from the floor area to the breathing zone. η_e describes the utilized fraction of the possible concentration difference between the floor and a neutral point in the breathing zone height.

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